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Measurements and analysis of reverberation and clutter data

Final Report for ONR Award N00014-03-1-0420, FY 03-06

Dale D. Ellis

Prepared for:
US Office of Naval Research
875 North Randolph Street, Suite 1425, Code 321 OA
Arlington, Virginia 22203-1995, USA

Defence R&D Canada – Atlantic

External Client Report
DRDC Atlantic ECR 2007-065
April 2007

Canada

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Principal Author

Dale D. Ellis

Dale D. Ellis

Approved by

Heard A/H/US

Neil Sponagle
Head/Underwater Sensing

Approved for release by

J. L. Kennedy CSci

for Kirk Foster
Chair/Document Review Panel

Abstract

This report describes the objectives and some of the results from a three-year joint collaboration between DRDC Atlantic and the Applied Research Laboratory of The Pennsylvania State University to analyze and model reverberation data. Reverberation data up to 4 kHz had been collected on towed arrays during the initial (1996–2002) NATO MILOC Rapid Environmental Assessment exercises and more recent JRPs (Joint Research Projects) between the US, Canada, and SACLANTCEN (now NURC, NATO Undersea Research Centre). Preliminary analysis and modeling of the data had been conducted, and reported at various conferences. For this project the data were analyzed and modeled in more detail, and the results reported in formal journal publications. Experiments were designed and conducted as part of a multi-ship trial in the Mediterranean in 2004, using arrays with directional sensors to perform left-right discrimination. A fast forward reverberation model was developed, suitable for inversion of environmental parameters in shallow water. Towed array beam patterns were incorporated, including the effects of directional sensors; results are presented showing the effects of cardioid and limaçon sensors. The model has also been extended to model echoes from targets and scattering features; preliminary comparisons with data from 2004 have been made. Future work includes a follow on JRP and clutter experiment in 2007, and extensions to the model for quantitative analysis of clutter scattering strengths.

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Executive summary

Measurements and analysis of reverberation and clutter data

Dale D. Ellis; DRDC Atlantic ECR 2007-065; Defence R&D Canada – Atlantic; April 2007.

Background: This report describes the objectives and some of the results from a three-year joint collaboration between DRDC Atlantic and the Applied Research Laboratory of the Pennsylvania State University to analyze and model reverberation data. Preston and Ellis had collected reverberation data up to 4 kHz on towed arrays during earlier (1996–2002) NATO MILOC Rapid Environmental Assessment exercises and more recent JRPs (Joint Research Projects) between the US, Canada, and SACLANTCEN (now NURC, NATO Undersea Research Centre). Preliminary analysis and modeling of the data had been conducted, and reported at various conferences. Some work on inverting for acoustic properties had been done.

Principal results: For this project the data were analyzed and modeled in more detail, and the results reported in formal journal publications. Experiments were designed and conducted as part of a multi-ship trial in the Mediterranean in 2004, using arrays with directional sensors to perform left-right discrimination. A fast forward reverberation model was developed, suitable for inversion of environmental parameters in shallow water. Towed array beam patterns were incorporated, including the effects of directional sensors; results are presented showing the effects of cardioid and limaçon sensors. It has also been extended to model echoes from targets and scattering features; preliminary comparisons with data from 2004 have been made. A follow-on JRP (2006–2010) has been incorporated in the NURC Scientific Programmme of Work.

Significance of results: From an operational perspective, clutter is viewed as one of the most important problems facing active sonar in shallow water. The long-term objective of this work is to better understand and model reverberation and clutter in shallow water environments, and to develop techniques for Rapid Environmental Assessment and environmentally adaptive sonar. Parts of the research have been incorporated into a DRDC TIAPS (Towed Integrated Active-Passive Sonar) Technology Demonstrator, which has been evaluated in ASW exercises against submarine targets. The work on clutter is related to the DRDC effort in Auralization and co-operative work with TTCP and other ONR efforts.

If the target echo model can be validated, this could be a useful method for estimating the target strength of clutter features – and even submarines – in multipath shallow water environments.

Future work: The collaboration has been extended to 2009. The previous focus was reverberation; now the emphasis will move to clutter. The PI will participate in the Clutter '07 and BASE '07 trials in the Mediterranean. The modeling effort will focus on quantitatively modeling some of the clutter features.

The initial results from the Matlab/Orca reverberation model compared well with others at the 2006 ONR Reverberation Modeling Workshop. The PI will work with Preston on further developments, possibly extending it to range-dependent bistatic geometries. The fast reverberation model still needs to be inserted into the simulated annealing inversion procedure, where it has the potential to speed up execution considerably at low frequencies. The focus of 2008 Workshop will partially determine the direction of our collaborative modeling work.

Future work includes a follow-on JRP, clutter experiment in 2007, and extensions to the model for quantitative analysis of clutter strengths.

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1 LONG-TERM GOALS

The long-term goal of this work was to better understand and model reverberation and clutter in shallow water environments, and to develop techniques for Rapid Environmental Assessment (REA) and environmentally adaptive sonar.

It was closely allied with other ONR efforts in Boundary Characterization and Geoclutter, the DRDC programs in REA and Auralization, and several US-Canada-NATO joint research projects.

2 OBJECTIVES

The objectives of this effort were:

- to analyze data from a number of previous reverberation experiments
- to prepare a number of manuscripts for publication
- to develop an efficient reverberation model that handles beam patterns and is suitable for inversion
- to design experiments for a 2004 sea trial
- to prepare for follow-on joint work with NURC and other collaborators.

This project was a joint collaboration between DRDC Atlantic (Defence Research & Development Canada – Atlantic) and ARL/PSU (Applied Research Laboratory of The Pennsylvania State University) to analyze and model reverberation and clutter data in shallow water. It allowed the PI to spend approximately three months each year at ARL/PSU. The collaboration leverages programs in Canada, US, as well as JRPs (Joint Research Projects) with the NATO Undersea Research Centre (NURC). The primary effort was analysis and interpretation of data, together with development and validation of improved modeling algorithms. With regards experimental results, the main objective was to analyze and model reverberation data received on towed arrays during the Boundary and Geoclutter sea trials conducted over the past few years. Several manuscripts were prepared for publication in refereed journals and more are in progress. One focus was the performance of directional sensors in towed arrays – specifically the NURC and ONR triplet arrays and the DRDC array with combined omnidirectional and dipole sensors. A fast shallow water reverberation model was extended to include beam patterns, and a sonar model that includes target echo has been developed using a similar normal mode formulation. This latter model is currently being validated. Experiments were designed and executed for the 2004 NURC-Canada-US Boundary Characterization trial in the Mediterranean. Some data have been analyzed and more work is in progress. A follow-on US-Canada-NURC JRP has been approved, and experiments are being designed for the 2007 clutter experiment in the Mediterranean.

2.1 Background

Dr Ellis (from DRDC Atlantic) and Dr Preston (from ARL) have a long history of collaboration going back to their time together at SACLANTCEN (now NURC) in the 1990s. Dr Preston has primarily been involved in reverberation measurements, and Dr Ellis in modeling, but each has had considerable experience in both. Ellis had developed normal-mode-based reverberation models [1, 2, 3] and applied them to his and other reverberation data to extract bottom parameters [4, 5, 6, 7, 8]. Preston had developed a polar display module (which is also in use at DRDC) and developed an automated inversion procedure [9, 10] using the Generic Sonar Model [11].

In 1995 Ellis and Preston had been invited by SACLANTCEN to participate as reverberation experts in three NATO MILOC REA exercises, Rapid Response, which took place in 1996, 1997, and 1998 [12]. Their responsibility was to use reverberation data received on a towed array to map bottom scattering features and extract bottom loss and backscattering strengths at various sites, in deep and shallow water. Their previously-developed techniques were partially automated, at sea analysis was performed, and the results were quite promising [6].

However, it was necessary to validate their manual inversion approach, which involved modeling the reverberation and estimating the bottom parameters from a manual inversion procedure; direct measurements of scattering were needed. A JRP on Boundary Characterization was proposed by US, Canada, and SACLANTCEN/NURC to undertake direct bottom measurements and compare them with the REA techniques. It was accepted in 1999, and three sea trials were conducted: in 2000 and 2002 in the Mediterranean, and 2001 on the New Jersey Strataform area and on the Canadian Scotian Shelf. Further automation of the inversion procedure for bottom parameters was developed by Preston [9, 10]. In parallel with these JRP activities, ONR held a specialists' workshop [13], developed a reverberation and geoclutter program, and had a towed array of triplet elements developed in time for a TTCP[1] multistatics trial in 2002.

The 2001 experiment was closely connected with an ONR Geoclutter trial, and the Canadian *R/V Quest* participated in the Boundary portion. These measurements were quite successful, and were reported in a workshop proceedings [14] and presentations at a special session of the Acoustical Society of America [15, 16].

As well, a follow-on JRP by Canada-US-NURC on environmental adaptation for multistatic sonar had been proposed and accepted for the years 2003-2005. The focus was further analysis of the 2000–2002 Boundary experiments, with an additional joint trial in 2004 when the Canadian *R/V Quest* transited to the Mediterranean for direct bottom measurements and reverberation analysis, in co-operation with the NATO *R/V Alliance* and

[1]The Technical Cooperation Program, whose members are Australia, Canada, New Zealand, United Kingdom and United States.

supporting vessels.

In summary, the Rapid Response and Boundary Interaction sea trials had been an intensive measurement program. Preliminary analysis of data had been done by Ellis and Preston and reported at various meetings and conferences, often as invited papers or in special sessions or workshops [5, 7, 8, 17, 18, 19, 20, 21]. However, the data needed more detailed analysis and formal reporting as journal articles.

3 APPROACH

The PI spent three months per year at ARL/PSU, conducting joint research with scientists in Dr David Bradley's research group, primarily with Dr. John Preston. Additional collaboration took place throughout the year in their own institutions. DRDC Atlantic has generally funded Dr. Preston annually for two weeks of research in Canada. The main objective was to analyze, model, and interpret data received on towed arrays during reverberation and clutter sea trials. The primary outputs of the collaboration were manuscripts for joint publications in refereed journals. Secondary outputs were improved models and algorithms.

Previous analysis had been based almost exclusively on data sets using explosive sound sources, and received primarily on the SACLANTCEN low frequency Prakla array (< 1500 Hz) with omnidirectional elements, and to a lesser extent the mid-frequency MF array (up to 4 kHz). This project emphasized examination and interpretation of data from several towed arrays with directional elements – specifically the NURC and ONR cardioid arrays with triplets of omnidirectional elements and the DRDC DASM (Directional Array Sensor Module) array with omnidirectional plus dipole sensors. Of particular interest was the new ONR-ARL/PSU cardioid Five-Octave Research Array (FORA). Models were extended to compare the performance of these arrays. Data from the Boundary '04 and BASE '04 sea trials were and continue to be analyzed along the lines of previous experiments [5, 6, 7, 14, 18, 22, 23]. Experiments are being designed for the 2007 joint US-Canada-NURC Wideband LFAS (Low frequency Active Sonar) Clutter Characterization Experiment in the Mediterranean.

As part of the analysis, a fast shallow-water reverberation model [3] based on normal modes [1] was extended to a fast shallow-water "sonar" model that includes target echo [24] and feature scattering. Like the reverberation model, it is computationally-efficient and includes the 3-D effects of towed array beam patterns [25], signal excess, and time-spreading in order to permit direct comparison with experimental measurements. The objective is to quantitatively invert, not just for bottom loss and scattering [4, 9, 10, 24], but for the target strength of discrete clutter features. It is hoped that the model may be validated against more computationally-intensive "physics-based" models developed by other researchers.

It should be noted that the proposed program of work was more than could be performed during the time allocated for this proposal. However, additional work was be done at both ARL/PSU and DRDC Atlantic. The joint collaboration under this proposal made a significant contribution to the overall Boundary Interaction and Clutter programs at both institutions.

4 WORK COMPLETED

4.1 Tool building

At ARL/PSU there is a dedicated data processing equipment suite consisting of both DEC and Compaq workstations running Unix, DLT (digital linear tape) and Exabyte tape drives, color printers, and special software packages such as MATLAB and UNIRAS. At DRDC Atlantic, there is a similar system based on Linux. Macintosh laptops and fast G5 PowerPC processors are used in both institutions, and taken to sea, for data processing with C and Fortran programs, and with MATLAB, IDL or other graphics software.

During the past 3 years Preston's processing system has migrated from DEC/Compaq to Linux based. The acoustic models were migrated as required from vendor-specific flavors of Fortran to standard g77 or g95.

Obtaining quantitative results from the directional arrays was much more difficult than anticipated. Neither the NURC algorithm for cardioids [26, 27] or the DRDC algorithm for omni-dipoles seemed to be quantitatively calibrated for broadband processing. Preston has submitted a journal article for triplet array calibrations [28], and the DRDC omni-dipole calibration is being carried out under contract [29, 30]. For quantitative results on the DRDC array, we translated DRDC data [31] into NURC format and used the beamforming algorithm of Hollett and Preston implemented at DRDC Atlantic [32].

5 International collaboration

In collaboration with colleagues at their various institutions, a new US-Canada-NURC JRP "Characterizing and reducing clutter in broadband active sonar" has been accepted by NURC for their Scientific Programme of Work (SPOW), which includes a sea trial in 2007. The four-year JRP effort seeks to provide a characterization of clutter that substantially improves the understanding of its mechanisms and its spatio-temporal properties at mid-frequencies (primarily 0.5-5 kHz). The emphasis of the JRP will be on developing observational and modeling strategies for identifying, characterizing and reducing seabed clutter, and the vetting of those strategies through two at-sea experiments. The results will serve as the basis for evaluating and refining signal-processing algorithms for determining and controlling the impact of clutter on active sonar system performance.

5.1 Progress in inversion

The manual inversion procedure [6] employed in the REA sea trials seems to work reasonably well, but is quite labor-intensive. Preston's automated inversion [9, 10] involves Unix scripts and links to an external program, the Generic Sonar Model (GSM).

It was proposed that the fast inversion model use the simulated annealing approach, and incorporate an imbedded normal mode code [1] and a reverberation subroutine instead of writing files and spawning a process to run GSM. The procedure is somewhat akin to the single-hydrophone procedure of Ellis and Gerstoft [4], but adapted for handling beam time series of towed array data. Towed array beam patterns [25] have been added to the fast reverberation model, including recent cardioid enhancements [33], and the model is ready for incorporation into the inversion package.

Bistatic reverberation models are too slow for inversion, but model-data comparisons will be made using ray-based models, e.g. GSM [11], or normal-mode models, e.g. OGOPOGO [2, 34]. Range-dependent reverberation modeling will be investigated, using adiabatic modes [35], or the range-dependent version of GSM – CASS/GRAB [36, 37]. Automated inversion is probably not feasible at present for these environments.

5.2 Sea trials

Experiments were designed for Boundary '04 conducted in the Mediterranean in May-June 2004. Figure 1 shows a polar plot of reverberation data from the Boundary 2000 experiment that was prepared by Preston [38] and used in the planning for Boundary '04.

Figure 2 shows a beam time series from the Boundary/BASE '04 trial. It shows a rectangular plot of the beam time series of the reverberation, noise, and feature scattering received on a towed array deployed on the Malta Plateau south of Sicily in June 2004. The source is a 0.8 kg SUS (Sound Underwater Source[2]) charge dropped from the stern of the Canadian research vessel, *CFAV Quest*. The receiver is the DRDC Atlantic DASM (Directional Acoustic Sensor Module) array, which has 96 pairs (at 0.5 m spacing) of omnidirectional and dipole sensors to allow resolution of array "left-right" ambiguity. Data were extracted using the DRDC Atlantic Sonar Test Bed (STB) for the one-third-octave band centered at 1000 Hz. For the event shown in Fig. 2 the array was at location N 36° 27.0′ E 14° 44.3′ on a heading of 266°. Illustrated are 160 beams spaced equally in cosine over the 360° azimuth; beam 1 is forward endfire, beam 41 is right broadside, beam 81 is aft endfire, and so on to beam 160, 12.8° left of forward endfire. The time is adjusted to 0 s at the time of arrival of the (overloaded) main blast; the precursor is some interaction of the SUS detonation on the tow cable. The high intensity reverberation is shown in red, decaying through yellow, to the ambient noise background in blue. The horizontal yellow lines present before the

[2]This expansion of SUS is from [39, p.165]; "Signal Underwater Sound" is also commonly used.

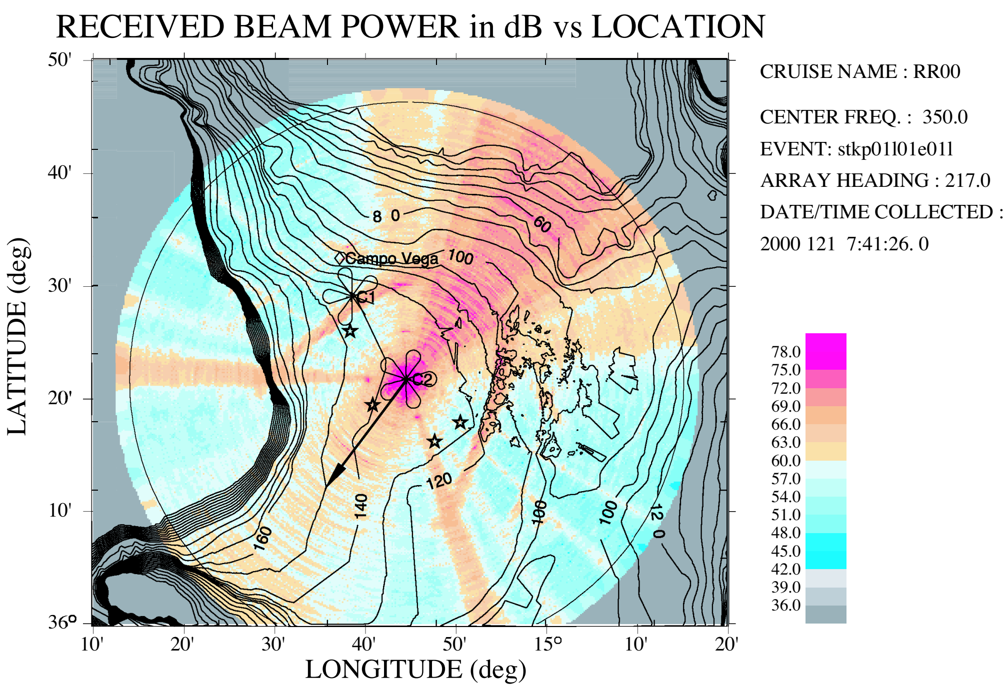

Figure 1: *Polar plot of towed array reverberation data from the Malta Plateau, illustrating locations of various clutter features (stars). The source was a 0.8-kg SUS charge processed in a 50-Hz frequency band around 350 Hz. The towed array location at the instant of the detonation is the base of the arrow, and the heading is the direction of the arrow. The ship tracks are shown as "petal patterns" around Sites C1 and C2; the diamond is the Campo Vega oil rig and tender; the color scale shows the received signal level in dB re 1 $\mu Pa^2/Hz$.*

main blast, and re-appearing later out of the reverberation, are noise from nearby ships. In addition to the overall reverberation, a number of scattering features also appear. The Ragusa Ridge shows up at aft endfire at 20 s, and later on adjacent beams. The echoes from the Campo Vega drilling rig and oil tender at 18 and 20 s appear on beams 14–18, and reflections from two "BBN targets" [40] appear at 10 and 11 seconds on beams 97–102. Some of the received signals are quantitatively discussed in the Section 6.2 below.

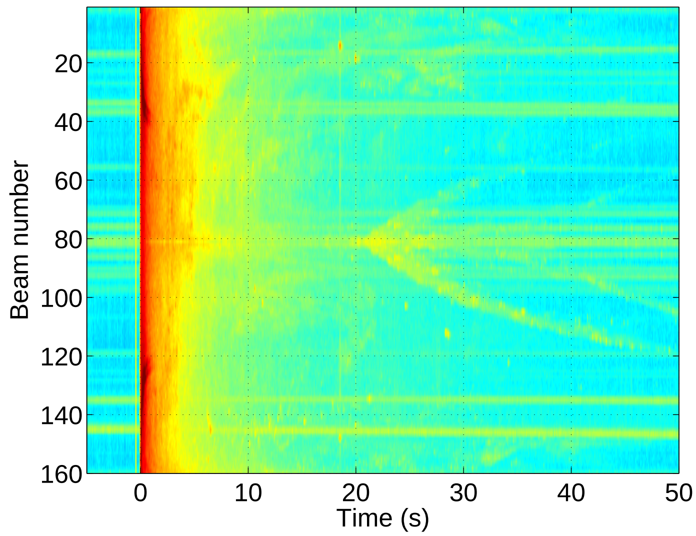

Figure 2: *Beam time series for event SUS1. The intensity scale ranges from 120 dB (red) to 40 dB (blue).*

5.3 Research accomplishments

Two manuscripts from previous collaboration on the 2000-2003 Boundary Interaction Joint Research Project were published in the IEEE Special Issue on Interaction of Low- to Mid-Frequency Sound with the Ocean Bottom [23, 38].

A comparison was made between the effect of cardioid beamforming versus limaçon beamforming on reverberation received on a towed array [41]. Some highlights are shown in Section 6.1 below.

The fast normal mode reverberation model (NOGRP) was extended (and renamed Rosella) to include beam patterns and to handle target echo and signal excess calculations. Initial comparison was made with towed array reverberation and feature-scattering data obtained in the Boundary/BASE '04 sea trial in the Mediterranean [33]. Some highlights are shown in Section 6.1 below.

Initial work was done in extending the normal-mode reverberation model to handle scattering from a basement interface, and make comparisons with an energy flux model. A journal paper is in progress.

A version of the fast normal-mode approach was implemented using the ORCA normal-mode model together with Matlab scripts for the reverberation calculations. Comparisons were made with NOGRP/Rosella and the Generic Sonar Model [11] for a few simple test cases. More comparisons were made and a bistatic version recently developed using the formulation in OGOPOGO [2]. Initial results were presented at the ONR Reverberation Modeling Workshop in Austin in November 2006 [42].

6 RESULTS

6.1 Effect of directional sensors

An investigation was made on the reduction of reverberation by arrays of directional sensors [41]. Figure 3 shows polar plots of the various beam pattern responses in the horizontal plane, for a 15-wavelength array. In the left plot, the linear array has equal response (blue solid) at 60° and 300°; when multiplied by the broadside cardioid (green dash-dot line), the combined response (red dashed line) has a much reduced response at 300°, which is only obvious on a dB plot (middle). In the right plot, the linear array has equal response (blue solid) at 30° and 330°, the normalized limaçon response (green dash-dot line) has a null at 330° and the multiplied response (red dashed line) has a single lobe at 30°. Even on a dB plot (not illustrated), the limaçon shows no ambiguous beam.

The limaçon beamforming can be easily implemented with omni/dipole sensors as used in the DRDC DASM array. It is not obvious that the triplet sensors in cardioid arrays can be used to produce a null in the ambiguous beam over a significant bandwidth. The limaçon processing requires the null be steered in the direction of the ambiguous beam, so a different limaçon must be used for each beam.

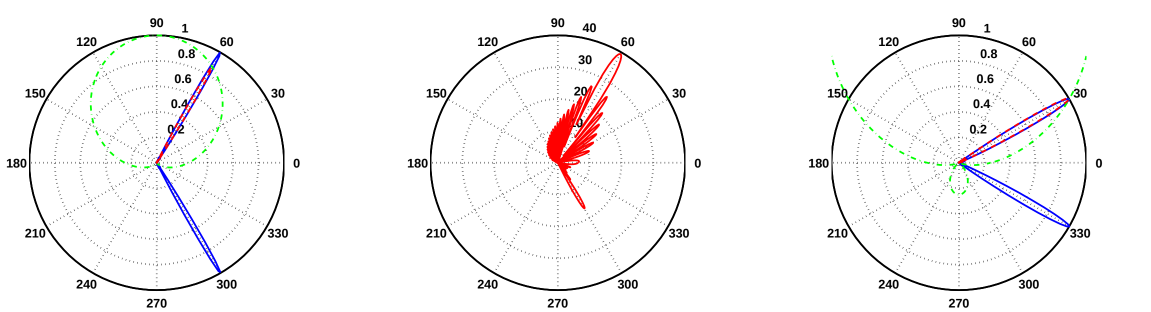

Figure 3: *Polar plots of beam patterns: (left) including cardioid response; (middle) normalized response as a dB plot; (right) including limaçon response. The array heading is 0°.*

Figure 4 compares the effective reverberation response of arrays with omnidirectional elements with arrays of cardioid and limaçon sensors. At broadside (left graph) the car-

dioid and limaçon are identical, and lower than the response for onmidirectional elements. Note that there is not a uniform 3 dB difference as one might naively expect from perfect left/right discrimination; the effective beam pattern is flatter (as a function of vertical angle) for the cardioid/limaçon. If one is using the broadside beam for inversion, it will be important to use the correct effective beam pattern, or else the differences will be attributed to the bottom loss (and result in misleading geoacoustic estimates). Away from broadside (right graph), the cardioid and limaçon arrays produce different results, with the limaçon producing lower reverberation response over most of the angles, and a much flatter response over the vertical angles of interest between the "cusps" (±30°, for a beam 60° from broadside).

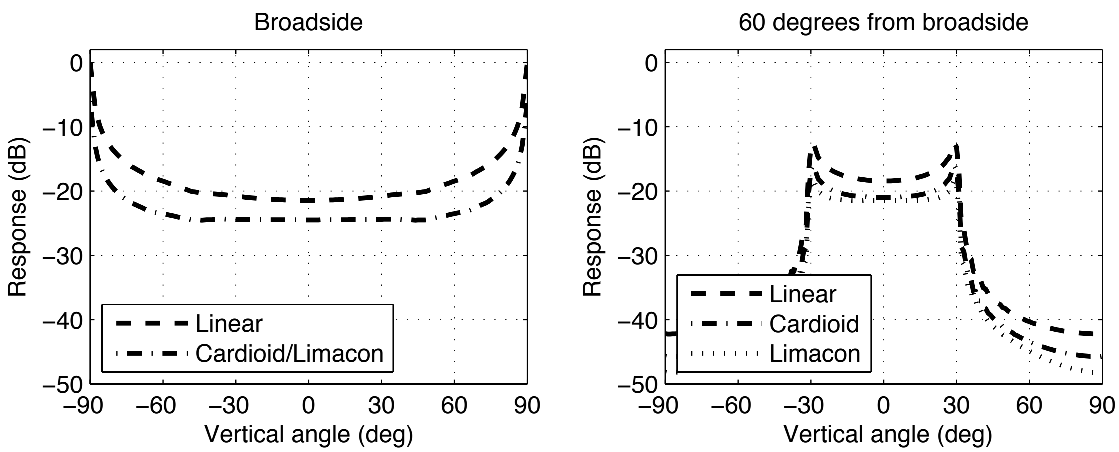

Figure 4: *Effective beam patterns for a 44-wavelength array: (left) broadside; (right) 60° from broadside.*

Figure 5 shows the corresponding reverberation response, using the beam patterns of Fig. 4. As one would have anticipated from Fig. 4, at broadside (left graph) the linear array provides over 20 dB reduction of the reverberation compared to a single omnidirectional sensor; the cardioid/limaçon sensors provide another 3 dB reduction of the reverberation. Note, even 60° from broadside (right graph) the limaçon sensors, compared to the cardioid sensors, produce only a small additional reduction of reverberation. Figure 3 indicated that limaçon sensors will be much more effective at reducing clutter on the ambiguous beam, but this has not yet been quantified; the Rosella target echo model could be readily adapted to investigate this.

6.2 Target echo and signal excess modelling

The normal mode reverberation model was extended to handle beam patterns, target echo, and signal excess calculations. First, the reverberation data on a quiet beam – e.g., no shipping noise and no major scattering features – was fitted by the model to estimate the scattering strength and bottom reflection loss. Then, the resulting geoacoustic properties were used in the target model to predict the target echo. Figure 6 shows predictions from

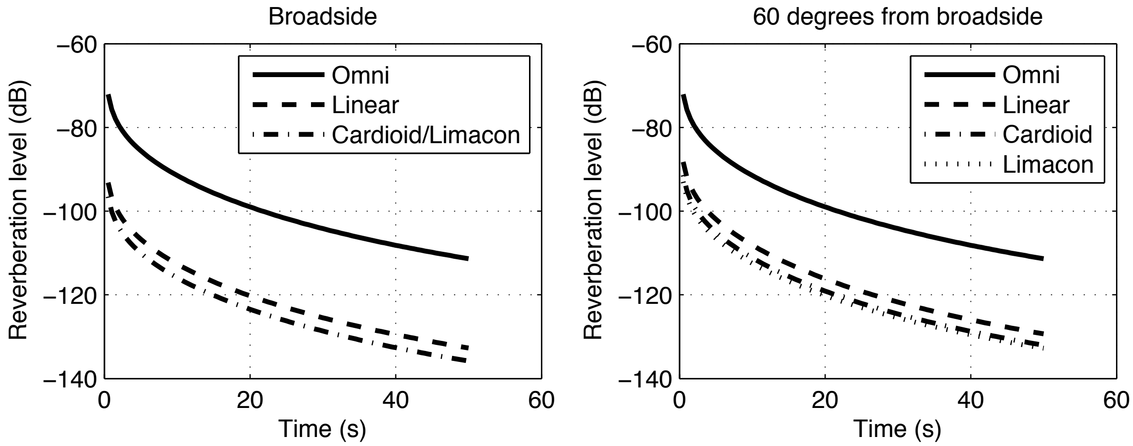

Figure 5: *Reverberation predictions: (left) omni and broadside beams; (right) omni and beams 60° from broadside.*

the Rosella model compared with data taken in the Boundary / BASE '04 sea trials in the Mediterranean [33]. In the left graph, the target strength of Campo Vega (at 18 s) and oil tender (at 20 s) was estimated from our model predictions to be 36 dB. In the right graph, echos from two BBN reflectors [40] appear at 10 and 11 s. The target strength estimated from our predictions was 19 dB, about 7 dB higher than expected from the BBN specification sheet (for a 30 m air-filled hose). The difference could be due to vertical directivity pattern of the BBN hose, or 3 to 4 dB errors in the estimated transmission loss, but more validation of the model needs to be done as well.

7 IMPACT/APPLICATIONS

From an operational perspective, clutter is viewed as one of the most important problems facing active sonar in shallow water. The long-term objective of this work is to better understand and model reverberation and clutter in shallow water environments, and to develop techniques for Rapid Environmental Assessment (REA) [12, 43] and environmentally adaptive sonar. Parts of the research have been incorporated into the DRDC TIAPS Technology Demonstrator which has been evaluated in ASW exercises against submarine targets. The work on clutter is related to the DRDC effort in Auralization and co-operative work with TTCP and other ONR efforts.

If the target echo model can be validated, this could be a useful method for estimating the target strength of clutter features – and even submarines – in multipath shallow water environments.

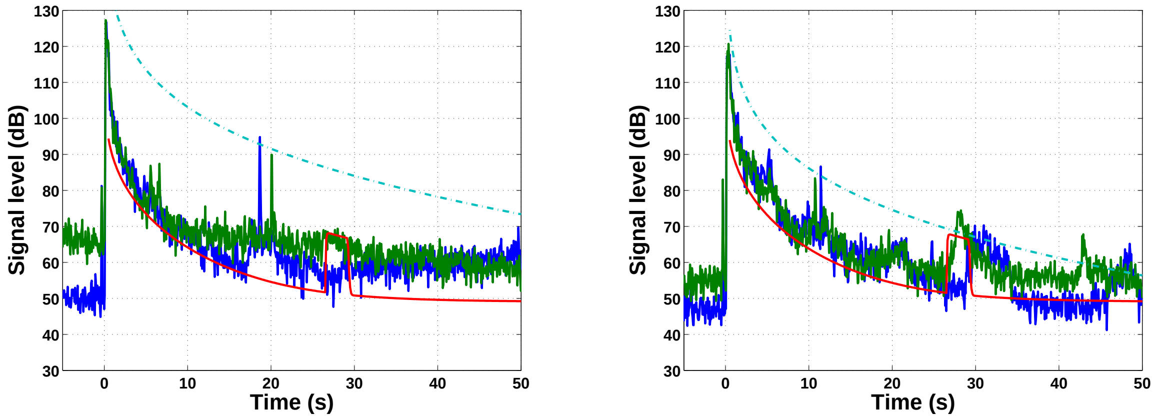

Figure 6: *Comparison of target echo model (dotted line) with echoes on two beams (blue, green) from Campo Vega oil rig and tender (left) and BBN targets (right). The red curve is fitted to the background reverberation, with an arbitrary enhancement of 20 dB between 26 and 29 seconds.*

8 RELATED PROJECTS

The most closely related projects are the US-Canada-NURC Joint Research Projects, and related experiments which receive substantial funding from ONR: the Boundary Characterization JRP (2000–2002), the Environmentally Adaptive Sonar JRP (2003-2005), and the present Wideband Clutter Characterization JRP (2006-2010).

DRDC Atlantic has a number of related projects. The most directly related is the Clutter Auralization TIF. The TIAPS project and Sonar Test Bed are low-frequency active sonar Technology Demonstrators that are also closely related. This ARL/PSU-DRDC collaboration began with REA, and there is a good connection with the DRDC REA Project. The PI is also helping to implement reverberation and target echo features in the Virtual Ship stimulator.

Joint collaboration between ARL and DRDC Atlantic has been ongoing, and DRDC has funded yearly visits by Dr. Preston, which have helped the DRDC Applied Research Program in Underwater Warfare.

As well, the personal interactions on this project facilitates collaborations on other projects among other scientists in the two laboratories.

Future work

The collaboration has been extended for another three years to 2009. The previous focus was reverberation; now the emphasis will move to clutter. The PI will participate in the

Clutter ’07 and BASE ’07 trials in the Mediterranean. The modeling effort will focus on quantitatively modeling some of the clutter features.

New work will emphasize examination and interpretation of data from several directional arrays (the NURC cardioid array, the DRDC DASM (Directional Array Module Sensor) array, and the ONR FORA array), and look at clutter received on highly directional towed arrays. Data from the Boundary ’04 and BASE ’04 sea trials will be further analyzed and experiments proposed for the 2007 sea trial.

The fast reverberation model is available to be incorporated and replace GSM in Preston’s simulated annealing inversion procedure, where it has the potential to speed up execution considerably at low frequencies.

The fast shallow water reverberation model has been extended to a fast shallow water “sonar” model using the same normal-mode techniques. Further development will be driven by the experimental program. It will be computationally-efficient and include the 3-D effects of towed array beam patterns, signal excess, and time-spreading in order to compare with experimental measurements. The objective is to be able to quantitatively invert for the strength of various clutter features. It can also be compared with more computationally-intensive physics-based models developed by other researchers. The emphasis on clutter will also lead to more emphasis on signal-processing issues.

The models [34, 42] compared well with others at the 2006 ONR Reverberation Modeling Workshop. The PI expects to participate in the second Reverberation Modeling Workshop in March 2008. The PI will work with Preston in refining the Matlab/Orca version of the shallow-water bistatic reverberation model; extension to range-dependent environments is a possibility using adiabatic normal modes [35]. The focus of the 2008 ONR Workshop will partially determine the direction of our collaborative modeling work.

Acknowledgments

John Preston has been a key player in this endeavor both as colleague and friend. Drs. David Bradley at ARL and Jeff Simmons at ONR were also instrumental in “making it happen” initially. Dr Ellen Livingston ensured the follow through.

The hospitality of the Applied Research Laboratory and The Pennsylvania State University is most appreciated in accommodating and welcoming this “alien” as a Visiting Scholar during his annual 3-month “mini-sabbaticals” at ARL/PSU. Kathy Shoemaker helped with a lot of the ARL paperwork, and ensured it got done. John and Jan Preston, as well as their cats Buster, Wally and Justin, regularly welcomed me into their house, particularly for Sunday dinner and specials on HBO. The academic and social activities around State College made it very much “a home away from home”.

Back in Nova Scotia my family took care of the home front. Colleagues at DRDC Atlantic filled in various holes created by my absence, and other potholes that had been created by my presence.

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This report describes the objectives and some of the results from a three-year joint collaboration between DRDC Atlantic and the Applied Research Laboratory of The Pennsylvania State University to analyze and model reverberation data. Reverberation data up to 4 kHz had been collected on towed arrays during the initial (1996–2002) NATO MILOC Rapid Environmental Assessment exercises and more recent JRPs (Joint Research Projects) between the US, Canada, and SACLANTCEN (now NURC, NATO Undersea Research Centre). Preliminary analysis and modeling of the data had been conducted, and reported at various conferences. For this project the data were analyzed and modeled in more detail, and the results reported in formal journal publications. Experiments were designed and conducted as part of a multi-ship trial in the Mediterranean in 2004, using arrays with directional sensors to perform left-right discrimination. A fast forward reverberation model was developed, suitable for inversion of environmental parameters in shallow water. Towed array beam patterns were incorporated, including the effects of directional sensors; results are presented showing the effects of cardioid and limaçon sensors. The model has also been extended to model echoes from targets and scattering features; preliminary comparisons with data from 2004 have been made. Future work includes a follow on JRP and clutter experiment in 2007, and extensions to the model for quantitative analysis of clutter scattering strengths.

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